TECHNICAL REPORT NO. 11789 (LL 143)

THE AMC '71 MOBILITY MODEL

U.S. ARMY TANK-AUTOMOTIVE COMMAND LABORATORIES

VOLUME I

SUMMARY REPORT

by The Staffs of the Mobility & Environmental Division, U.S. Army Engineer Waterways Experiment Station, & the Surface Mobility Laboratory, U.S. Army Tank-Automotive Command.

TACOM

MOBILITY SYSTEMS LABORATORY

U.S. ARMY TANK AUTOMOTIVE COMMAND Warren, Michigan

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July 1973

ABSTRACT

This report presents the AMC '71 Mobility Model, a comprehensive computerized simulation of the interaction of a vehicle, a terrain and an operator. This model represents existing technology (as of 1971) for predicting the performance of wheeled or tracked vehicles across any type of terrain. While the model involves several simplifying assumptions necessitated either by lack of more complete information or by practical limitations on complexity and computer capacity, when used judiciously, it is a useful tool for ground mobility analysis even in its present form.

Following a brief introductory section, input requirements are discussed. Next is presented a narrative description of the model's structure including the simulation of dynamic effects and the crossing of areal terrain and linear terrains such as streams. The basic model output is shown to be a number of predicted speeds for a given single vehicle in each of a number of subunits of the terrains. Speeds in individual terrain subunits can be used for the development of various outputs depending on the needs of the user.

Principal restrictions and limitations of the model are given. Finally, two important applications are described in order to illustrate some of the possible uses of the model.

Appendix A contains the complete listing and definition of the necessary terrain input data. Appendix B includes the same for the vehicle inputs. Appendix C contains flow charts, program listings and the necessary background information in sufficient detail for a programmer to reproduce the AMC '71 Model.

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I. FOREWORD

In the past, quantitative evaluation of vehicle off-road mobility was based on independent examination of single factors such as soft soil performance (drawbar pull/weight ratio or vehicle cone index), or the maximum speed that an average driver could tolerate while traversing rough terrain (V-ride), or the maximum vertical step height that a vehicle could climb, or the maximum slope that could be negotiated, and so on.

It was not possible, however, to account for all such important mobility impediments as they occur in concert over a geographic area and as they affect the vehicle in a combined way. The computation requirements to deal with all influences and their interactions were simply too great. The availability of modern computers now makes the necessary computations not only possible but practical.

Simulation or comprehensive mathematical modeling allows for the evaluation of the entire vehicle system (engine, transmission, suspension, weight, geometry, inertia, winching capacity, and so on) as it interacts with soil, vegetation, slopes, ditches, mounds and other features in a synergistic fashion. Thus, the fact that Concept A can climb twice as high a step as Concept B, for example, can be weighed in the light of the frequency of critical occurrence of step-like obstacles in a theater of operation for which appropriate terrain data are available.

At the request of the Environmental Sciences Branch of the Research Division, RD&E Directorate, US Army Materiel Command (AMC), the US Army Corps of Engineers Waterways Experiment Station and the US Army Tank-Automotive Command, beginning in December 1969, undertook to incorporate existing research and engineering knowledge of terrain-vehicle-man interactions into a comprehensive computerized simulation of

a vehicle moving across a complex piece of terrain. This task became part of a broad mobility research program, performed under the auspices of AMC, which pools the efforts of TACOM, WES and the US Army Cold Regions Research and Engineering Laboratory (CRREL). The first-generation simulation was completed in July 1971, and was designated the AMC '71 Mobility Model (AMC-71).

The model has been under continuous research, development and validation in the months since, and has already undergone a number of changes, extensions and improvements. More are in progress. The philosophy, structure and approach remain largely unchanged, however, and the utility of AMC-71 (the original version) has been demonstrated in several practical applications (17, 18, 19)*. Accordingly, it is useful to describe AMC-71 as of July 1971, which is the purpose of this report.

It is believed that AMC-71, or a similar comprehensive engineering model, is the proper modern tool for mobility evaluation. No future military vehicle concept study can be complete and credible without such a comprehensive mobility analysis.

II. OBJECTIVES

The immediate objective of this report is the presentation and documentation of the AMC-71 Vehicle Mobility Model in order to disseminate information pertaining to its general structure and to make the complete program listings available to potential users.

The overriding need in land mobility technology is for a valid, comprehensive methodology to support decision

*Numbers in parentheses denote references listed at the end of the text.

processes throughout the military materiel development cycle with analyses which realistically incorporate land mobility influences. From a broad viewpoint, the objective of this report is to document the status of one of the key components of the required comprehensive land mobility modeling methodology: the analytical simulation of the terrain-vehicle-man interaction.

III. RESULTS

The main results reported herein are (1) the formulation of the AMC '71 Vehicle Mobility Model, and (2) the establishment of a comprehensive computer program which implements the model and allows for the development of quantitative information on the mobility of a given vehicle in a selected geographic area.

Although the AMC '71 Vehicle Mobility Model is not a finished product, the model has already proved to be a useful tool in important studies whose objectives were the evaluation of concepts for a new Main Battle Tank (18), the assessment of the off-road/on-road performance of a group of standard and modified wheeled vehicles (17), and the mobility comparison of a wide range of towed and self-propelled artillery (19). Several other analyses of lesser scope have also been performed.

IV. CONCLUSIONS

The AMC '71 Vehicle Mobility Model can predict the cross-country speed of wheeled and tracked vehicles in a given geographic area when the area is properly quantified in terms of terrain factors affecting vehicle mobility. The model promises to be a particularly useful tool for:

a. Establishing mobility criteria which can ensure a desired level of performance in a specified geographic area.

b. Determining and comparing the expected performance of various vehicle concepts in a specified environment.

c. Studying the effect of design changes on the cross-country performance of wheeled or tracked vehicles.

The AMC '71 Vehicle Mobility Model has the potential to become part of a broader simulation, such as a complete battlefield effectiveness model or a comprehensive life cycle cost-effectiveness analysis.

Another important conclusion, reached while using the model for the studies mentioned in the previous section, is that the model, in its present form (AMC-71), is not yet suitable for unrestricted use. Outputs must be weighed by personnel with a thorough knowledge of the assumptions presently involved, who can critically examine apparent output anomalies to determine if they are artifacts of the simulation rather than valid reflections of reality, and, if so, can make legitimate corrections to appropriate model subroutines. Familiarity with the assumptions involved and judicious use of the output data, on the other hand, make the utilization of the model feasible, practical and desirable even at this early stage of development.

V. HISTORICAL BACKGROUND

Off-road vehicle mobility research has been systematically pursued by two major agencies within the US Army. The Corps of Engineers Waterways Experiment Station began investigating the trafficability of soft soils shortly after World War II. The Surface Mobility Division of the US Army Tank-Automotive Command (formerly the Land Locomotion Research Branch of the US Army Ordnance Corps) has been engaged in land locomotion research since 1954. These Army agencies and other US and foreign researchers representing private industry, universities and research institutes have generated an impressive pool

of information (cf. 1, 2, 3, 4). Problems related to soft-soil mobility, to the mechanics of obstacle negotiation, to mobility in the riverine environment, to driving through wooded areas, and to the limits of human tolerance to vibrations caused by travel over rough terrain have been explored and elucidated by theoretical analysis, by experimentation in the laboratory and by field testing. Sophisticated techniques for the characterization and measurement of terrain features influencing vehicle mobility have been developed (5).

The technology of terrain-vehicle mechanics is based on fundamental and/or empirical relationships describing the interaction of the terrain-vehicle-man system. It has been demonstrated that this technology can be effectively applied to design highly mobile vehicles (6), and that it is also useful for concept studies (7), design optimization (8), operations analysis (9), and the formulation of quantitative off-road performance specifications (10).

In the light of the complexity of the terrain-vehicle-man interaction, however, the existing analytical methodology is still relatively undeveloped. Many of the relationships currently employed to describe system performance are based either on unproven theoretical assumptions or on weakly supported empiricism. The limited experimental foundation for the current methods generally applies only to idealized conditions. In all, the science of terrain-vehicle mechanics remains in its infancy, and continuing effort is needed to make the technology a sound and proven tool for the engineering practitioner.

In December 1969, a unified program integrating all vehicle mobility research being performed under AMC auspices was initiated at WES, TACOM and CRREL. The unified program was designed to eliminate wasteful duplication of effort and to concentrate available resources towards the achievement of

common, end-item-oriented goals. Detailed plans for the program were formulated by the staffs of the participating research organizations, with the guidance of the AMC Ground Mobility Research Program Steering Committee.

The broad objective of the unified AMC Mobility Research Program is the development of performance-oriented engineering methodology for the design, selection and deployment of military vehicles. Such methodology must be based on a comprehensive analytical representation of the interaction of the terrain, the vehicle, and the human occupants. This representation, or simulation, must be fully validated on the basis of a systematic program of carefully controlled field tests.

It was estimated in 1969 that the development of a comprehensive simulation of the terrain-vehicle-occupant system, with field-demonstrated accuracy sufficient for purposes of detailed system design, would require a coordinated effort by WES, TACOM and CRREL of at least five years duration. (Due to subsequent funding cuts, the duration of the required effort will in fact be longer.) It was reckoned neither necessary nor desirable, however, to wait five or more years for the joint program to begin to pay off. Even an imperfect simulation, properly applied and interpreted, can produce findings of significant value to a broad community of users. The unified AMC Mobility Research Program was accordingly designed to be responsive to both long-term and short-term requirements.

The first step was the consolidation and synthesis of existing performance-prediction methodology. Available mathematical models for individual facets of system performance were reviewed and evaluated in terms of expected accuracy, input data requirements, and mutual compatibility. Selected submodels were then integrated, using existing interaction algorithms (11) and dynamic programming techniques (12), to produce a comprehensive digital computer

simulation which predicts the maximum cross-country speed of tracked or wheeled vehicles in any terrain environment. Results of the Mobility Environmental Research Study conducted by WES in the mid-sixties were of great help in the conceptual development of AMC-71 (5, 20).

The comprehensive simulation is called the "AMC '71 Mobility Model" (AMC-71). As the name suggests, the model is conceived of as the first generation of a family, whose descendants will be characterized by greater accuracy and ranges of applicability as subsequent research results become available.

Maximum practical speeds for a vehicle in subunits of a terrain, calculated from validated engineering relations, can be combined by suitable procedures to predice the performance of the vehicle along any given path in the real terrain and/or to accumulate a statistical representation of vehicle performance in the area as a whole. It is also possible to find the best route between the two points within the terrain, based upon such measures of effectiveness as least total travel time (highest speed-made-good).

VI. INPUT REQUIREMENTS AND TERRAIN UNITS

Cross-country performance depends on the terrain, the vehicle and the driver (and also the cargo in some cases).

The AMC '71 Mobility Model considers all important aspects of the terrain which influence cross-country movement of a single vehicle and establishes the maximum speed that the driver-vehicle system can practically attain while moving across the terrain at a given point.

Following is a list of terrain factors which must be specified quantitatively for the AMC '71 Model when treating areal terrain:

1. Surface type (fine-grained soil, coarse-grained soil, organic soil, or snow).

2. Soil strength in dry condition.

3. Soil strength in average condition.

4. Soil strength in wet condition.

5. Slope.

6. Approach angle of obstacles.

7. Vertical magnitude of obstacles.

8. Base width of obstacles.

9. Length of obstacles.

10. Spacing of obstacles.

11. Obstacle type (random orientation or parallel).

12. Surface roughness.

13. Spacing of trees of all stem diameters.

14. Spacing of trees for which stem diameter = 2.5 cm.

15. Spacing of trees for which stem diameter = 6 cm.

16. Spacing of trees for which stem diameter = 10 cm.

17. Spacing of trees for which stem diameter = 14 cm.

18. Spacing of trees for which stem diameter = 18 cm.

19. Spacing of trees for which stem diameter = 22 cm.

20. Spacing of trees for which stem diameter = 25 cm.

21. Recognition distance.

The following terrain factors are required to describe linear terrain units such as rivers, gullies, ravines and so on:

22. Left bank slope.

23. Differential bank height.

24. Right bank slope.

25. Water width.

26. Water depth.

27. Stream velocity.

Detailed definitions for these factors are found in Appendix A.

The vehicle characteristics required for the computations may be divided into three main categories:

1. Geometric.

2. Inertial.

3. Mechanical (such as gear ratios or engine torque versus rpm curve).

Since the model involves a complex system of relationships, the list of input data required to characterize the vehicle is extensive; presently 69 different vehicle parameters must be specified in all. These include, within the above three categories, final drive efficiency, tire or track dimensions, suspension compliance and damping characteristics, approach and departure angles and various dimensions and weights characterizing the magnitude and distribution of masses.

A detailed list of the required vehicle input data is given in Appendix B.

The driver is accounted for by considering:

1. Reaction time.

2. Recognition distance (listed among terrain factors).

3. V-ride limits (tolerance to rough ride: 6 watts of power absorbed by the driver's body due to vibration).

4. Vertical acceleration limit (2-1/2g when riding over single step-like obstacles).

5. Horizontal deceleration (2 g when knocking over a tree).

While the vehicle and driver characteristics do not change during the evaluation of a vehicle, the endless variability of a real terrain must be accounted for by a scheme which allows for specifying a finite set of terrain parameters and still represents the variation of the terrain adequately.

To make the task manageable, classes are stipulated for the numerical values of each relevant terrain factor. Class intervals are selected for each terrain factor under constraints of practical considerations in terrain data collection and mapping, plus the desirability that factor variations within a class not affect vehicle performance significantly. (See pages A17-A26, Appendix A). As long as the terrain factor remains between the upper and lower bounds of its class, it is considered to be constant and its value is assumed to be the average of the upper and lower bounds. (For example, if a slope within an area is between 5.1 and 10 percent, it is assumed that the terrain has a constant slope of 7.5 percent throughout the area.)

An area (or a length of linear feature) over which each of the terrain factors characterizing it (21 for areal terrain; 6 for linear) remains within a single class interval

is considered to be homogeneous and to represent a constant mobility impediment. Hence, the AMC '71 Mobility Model predicts a single constant maximum speed anywhere in this area (or a single required time to cross the linear feature anywhere along its length). Such an area or length is called an areal or linear terrain unit. When any one of the terrain factors transgresses the upper or lower limits of its class bounds, a different terrain unit is defined and a new speed attainable by the vehicle, or the crossing time, is calculated.

Thus, the main or basic output of the AMC '71 Model consists of one speed prediction for each areal terrain unit defined within a given geographic area and a crossing time prediction for each linear terrain unit defined.

Figure 1 depicts part of the areal mobility terrain unit map representing some terrain in Puerto Rico. The areal terrain units form irregular areas. Each bears a code number. Twenty-one constant terrain parameters are identified with each code number (see list on pages 7-8).

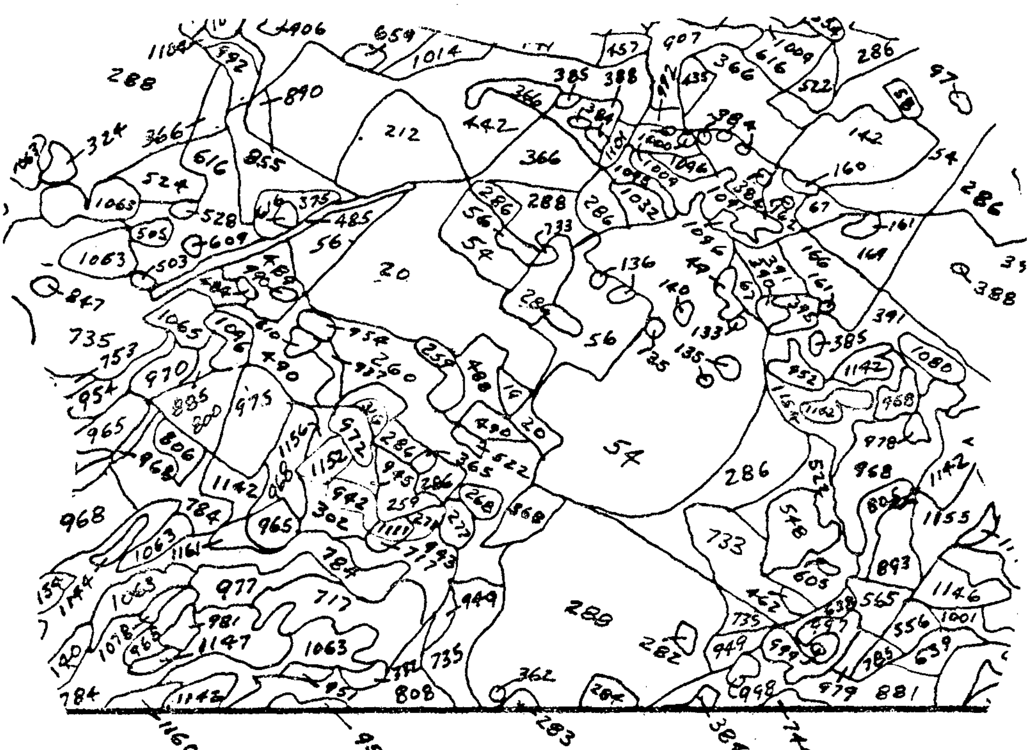


FIGURE 1

VII. MODEL STRUCTURE AND SUBROUTINES

The main output of the AMC '71 Mobility Model is vehicle speed. In general, speed may be limited or even made zero (NO-GO) by (1) inadequate engine and power train performance; (2) restricted traction due to weak soil or too small a contact area; (3) large obstacles; (4) restricted space between obstacles or trees; (5) inadequate traction to override trees or to cross obstacles; (6) excessive slopes; (7) deep water or swift current; (8) difficult river bank conditions (hang-up or lack of traction); (9) rough terrain which induces hard-to-tolerate vibrations; (10) obstacles and/or trees large enough to cause excessive acceleration or deceleration when overriding them; (11) imperfect visibility; (12) or any combination of the preceding causes. The model examines the full range of possible limiting vehicle-terrain-driver interactions to determine the maximum feasible speed in a suitably quantified terrain situation.

The model consists essentially of four computational modules:

1. Ride dynamics module.

2. Areal terrain-unit module.

3. Linear terrain unit module (stream-crossing).

4. Output module, which in its most basic form, simply lists maximum speeds attainable in each areal terrain unit and/or minimum corssing times for each linear terrain unit described in the input.

The output may be further processed to create vehicle speed distribution maps for the area under study, to generate statistics describing the vehicle's speed performance in the area, or to select optimum routes corresponding to given constraints and measures of effectiveness. The choice depends on the user's need.

The structure of the AMC '71 Model is illustrated in Figure 2.

1. Dynamics Module.

The dynamics module is used to calculate speeds as limited by the driver tolerance to vehicle motions induced in the vehicle when negotiating continuous terrain roughness and discrete obstacles. Areal terrain-unit descriptors include the root-mean-square (RMS) of the continuous terrain roughness, and the height of step-like obstacles found in the unit. Each is specified as lying within an appropriate class interval. In order to minimize computing time and computer core requirements, calculations of maximum speeds defined by driver tolerance at the mid-points of each RMS and obstacle height class interval are made externally, once and for all, in the dynamics module. Results are supplied to the areal terrain unit module as a part of that module's required vehicle data input.

The simulation of vehicle dynamics is necessarily complex. In the interest of expediency, the AMC '71 Model was initially programmed for four specific vehicles only, rather than for tracked and wheeled vehicles of general configuration. (Since the completion of AMC '71, however, generalized digital computer models have been established.) The four vehicles are: M60, Full-Tracked Combat Tank; M113, Full-Tracked Armored Personnel Carrier; M151, 4x4, 1/4-ton, Utility Truck; and M35, 6x6, 2-1/2 ton, Cargo Truck.

The vehicle dynamics module is described in detail in Appendix C. Briefly, the module computes limiting vehicle speeds due to occupant tolerance to vibration and shock. Its output is two sets of numbers. The first set contains limiting speeds over each continuous rough profile class. Experiments at TACOM have indicated that an average male's body cannot absorb more than six watts of vibratory

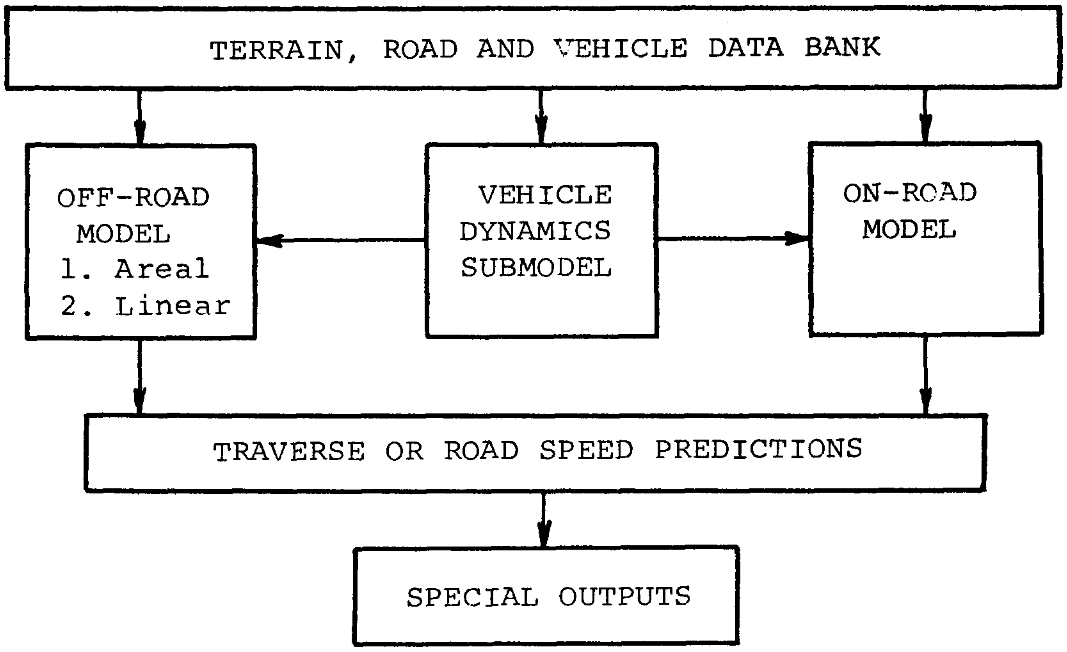


Fig. 2. General flow diagram of AMC-71 Mobility Model

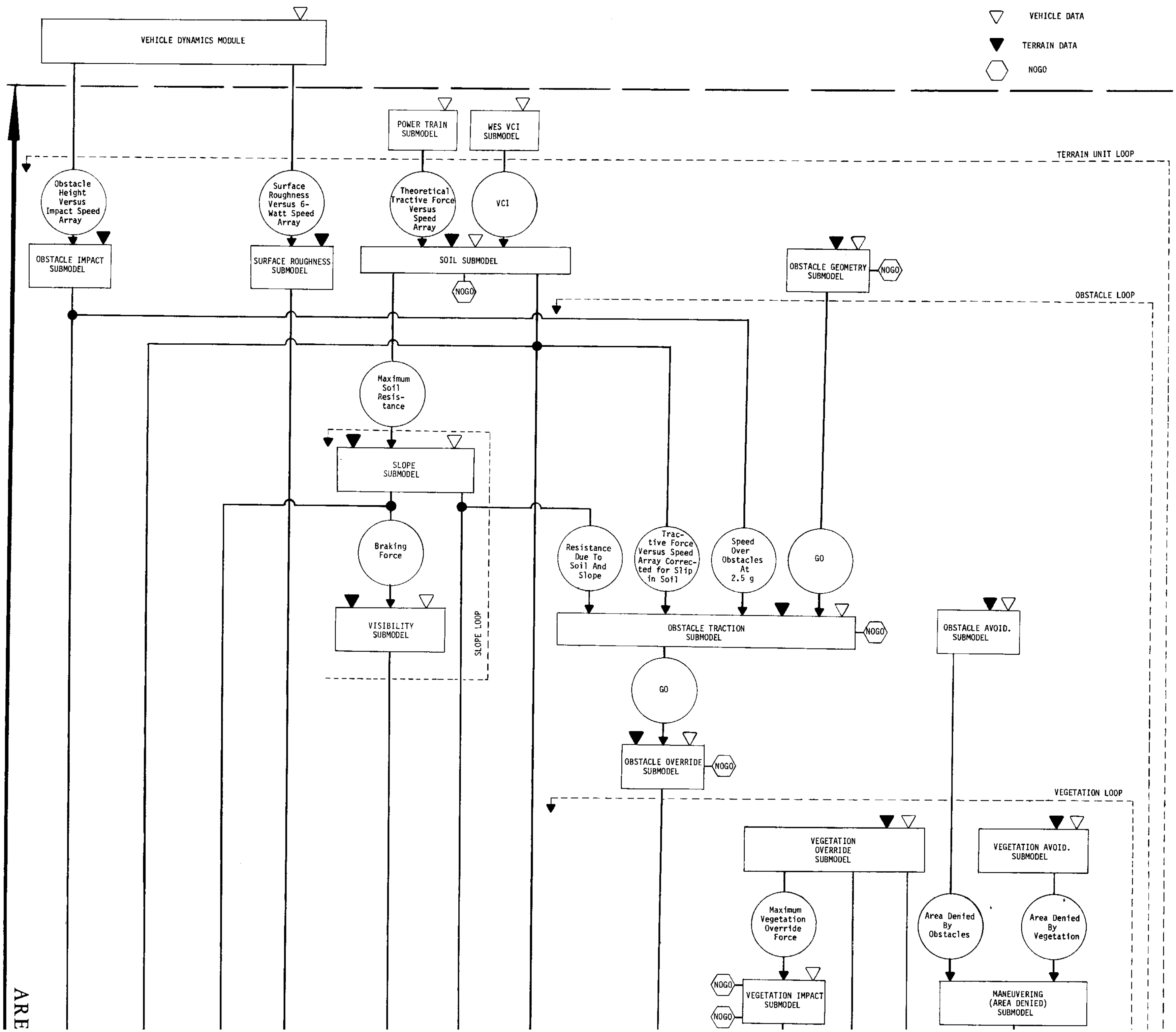
power without extreme discomfort (13). Thus, the module calculates a speed for each roughness class (defined by the root-mean-square elevation of the profile) at which the driver's body must absorb 6 watts of power. The equations make use of a deterministic representation of the profile with specified statistical characteristics, the characteristics of the suspension, vehicle geometry, and the vehicle's mass distribution. The computation is accomplished by iteration (e.g., various vehicle speeds are assumed and the absorbed power is calculated until the speed is found for which the absorbed power is just 6 watts).

The second set of numbers represent vehicle speeds at which the driver is exposed to a maximum of 2-1/2g vertical acceleration while crossing each of a series of single step-like obstacles. The module is used iteratively to find that critical speed for each vertical step height classes.

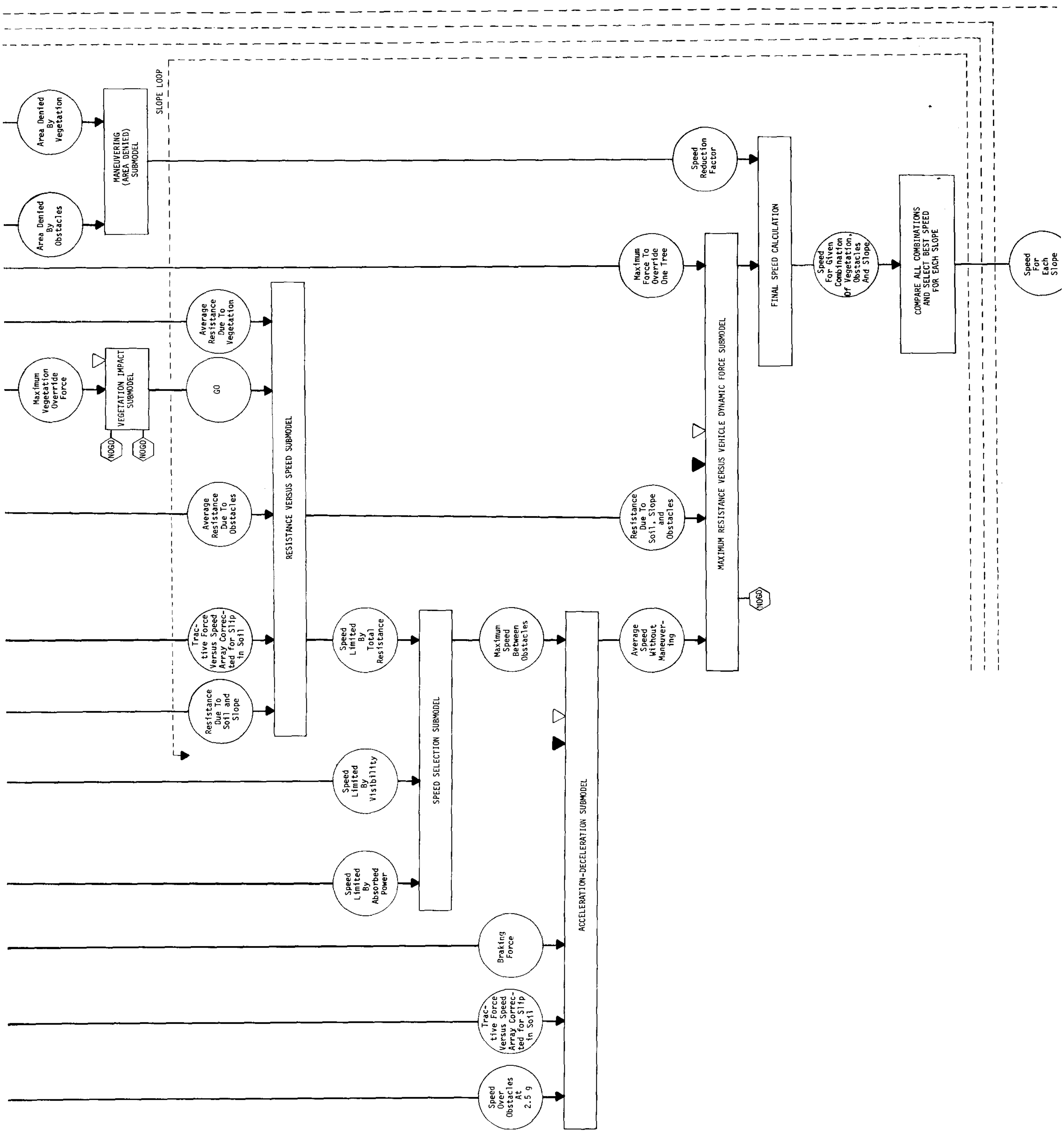
2. Areal Terrain-Unit Module.

Each terrain unit contains many other impediments in addition to rough terrain and step-like obstacles. Limiting speed values corresponding to these other factors, simply and in various combinations, are computed in the areal terrain module and considered along with the dynamics-limited speeds in determining the predicted maximum speed attainable in the terrain unit. The following discussion is illustrated by the flow chart shown in Figure 3.

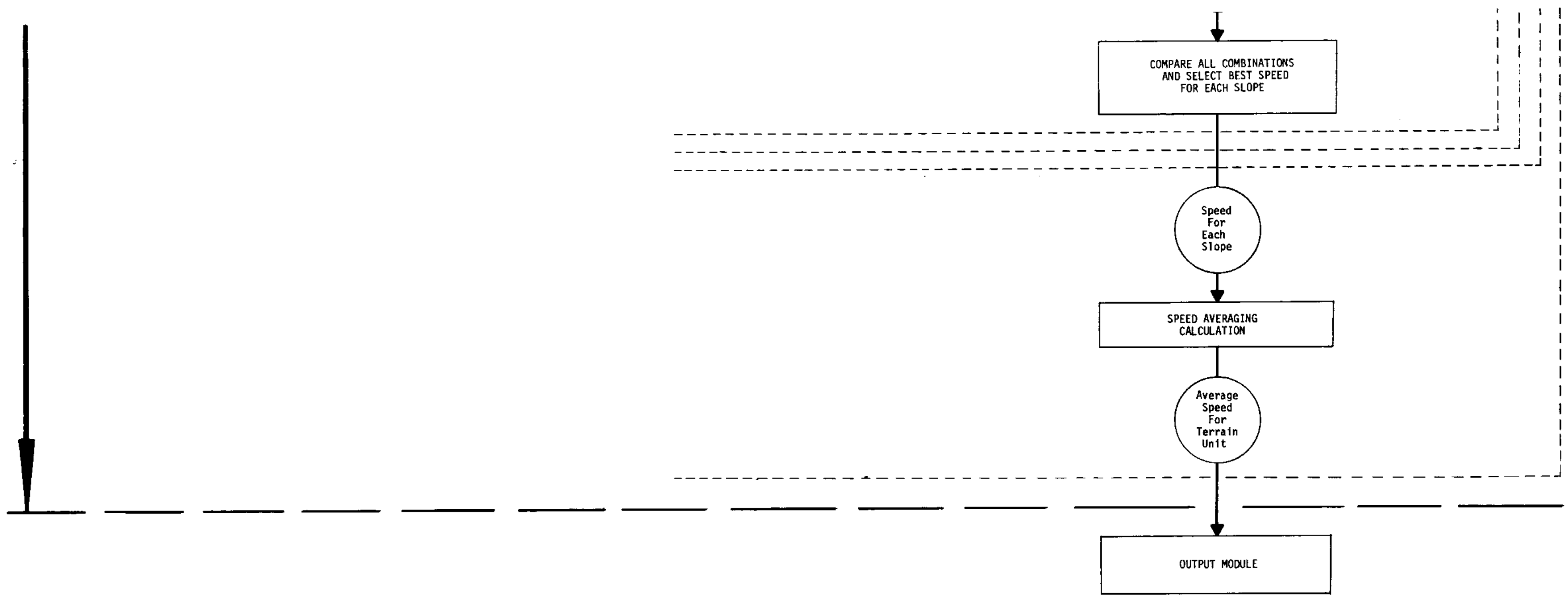
The first step is to input a file of vehicle parameters and a second file characterizing the terrain of interest as a series of terrain units described in terms of classes for each terrain factor. Since the terrain factors include separate class interval assignments for soil strength to reflect seasonal variation, each run is started by selecting the season for which the calculation is to be performed (wet, medium, or dry).


VEHICLE DATA
TERRAIN DATA
NOGO
VEHICLE DYNAMICS MODULE
POWER TRAIN SUBMODEL
WES VCI SUBMODEL
TERRAIN UNIT LOOP
Obstacle Height Versus Impact Speed Array
Surface Roughness Versus 6-Watt Speed Array
Theoretical Tractive Force Versus Speed Array
VCI
OBSTACLE IMPACT SUBMODEL
SURFACE ROUGHNESS SUBMODEL
SOIL SUBMODEL
OBSTACLE GEOMETRY SUBMODEL
OBSTACLE LOOP
Maximum Soil Resis-tance
SLOPE SUBMODEL
Braking Force
VISIBILITY SUBMODEL
SLOPE LOOP
Resistance Due To Soil And Slope
Trac-tive Force Versus Speed Array Correc-ted for Slip in Soil
Speed Over Obstacles At 2.5 g
GO
OBSTACLE TRACTION SUBMODEL
OBSTACLE AVOID. SUBMODEL
OBSTACLE OVERRIDE SUBMODEL
VEGETATION LOOP
VEGETATION OVERRIDE SUBMODEL
VEGETATION AVOID. SUBMODEL
Maximum Vegetation Override Force
Area Denied By Obstacles
Area Denied By Vegetation
VEGETATION IMPACT SUBMODEL
MANEUVERING (AREA DENIED) SUBMODEL
ARE

2 of 3



AREAL TERRAIN MODULE



FLOW OF AREAL TERRAIN MODULE

Figure 3

Next, the vehicle power train submodel is called upon to compute maximum available traction as a function of theoretical vehicle speed. Engine, transmission and drive line characteristics are used to calculate the torque that reaches the drive sprockets or the driving wheels of the vehicle in each available transmission gear. The torque at the sprocket or wheels is a function of engine rpm, so that this submodel produces final drive torque versus final drive rpm predictions.

Final drive torque is converted to maximum available traction by dividing it by the sprocket pitch radius (or tire rolling radius) and the rpm of the sprocket (or driving wheels) is correspondingly converted to theoretical vehicle speed. Thus, the power train submodel yields a series of pairs of numbers which define a theoretical (or maximum available) tractive force versus speed curve. This theoretical traction-speed relationship is valid for a vehicle which does not have tire and suspension hysteresis losses nor internal track losses and operates on a surface which offers no external motion resistance and induces no wheel or track slip.

The output of the power train submodel depends on vehicle characteristics only, hence, needs to be generated only once for each vehicle. Another vehicle characteristic, the vehicle cone index (VCI) is also calculated at this time.

The following calculations must be repeated for each terrain unit. The first step in this interactive procedure is to call the soil submodel which utilizes the outputs of the VCI submodel and of the power train submodel and produces an array of numbers representing "tractive force versus speed corrected for slip in soil". (This array is then further utilized by three different submodels according to Figure 3.) The "corrected tractive force curve" is a modification of the theoretical tractive force versus speed curve. The modification is necessary because available

traction is often limited by soil properties rather than by maximum available driving torque. In such cases the soil can only support a given tractive force, and if the vehicle attempts to exert more, the wheels (or tracks) will spin out. When the traction is lower than the upper limit defined by the soil-running gear interface conditions, the vehicle will operate at a slip which is greater than zero but less than 100 percent. In other words, there is some slip associated with each tractive force value below the maximum which the soil will support. The amount of slip depends on both vehicle and soil characteristics. The vehicle's speed will be reduced by the slip from the theoretical value to an actual one.

In addition to the corrected tractive force curve, the soil submodel also computes the resistance which the soil offers to the motion of the vehicle. It compares this resistance to the corrected tractive force curve. If resistance is greater than achievable traction at all speeds, NO-GO is assigned for the whole terrain unit.

Next, the slope submodel is used. Both uphill and downhill travel is considered. The motion resistance and tractive force versus speed curve are adjusted to account for the reduced normal force and for the presence of that component of the vehicle weight vector which is parallel to the slope. NO-GO is again assigned for the entire terrain unit if achievable traction is less than resistance at all speeds.

The outputs of the slope submodel are the resistance due to soil and slope and the effective braking force. The latter consist of two parts. The first part is equal in magnitude to the maximum tractive force which the soil will support and points in the direction opposite to the direction of motion. The other part is that component of the weight of the vehicle which is parallel to the slope. This force hinders braking when the vehicle moves downhill, but it is added to the braking force when the vehicle moves uphill.

The braking force is used in the visibility submodel. A "speed limited by visibility" is calculated on the basis that the driver of the vehicle must be able to stop within the recognition distance. The vehicle stopping distance is computed from the effective braking force and the driver's reaction time.

The "speed limited by visibility" is stored for later use.

Next, the computer examines obstacles and vegetation.

The obstacle geometry submodel checks the geometry of the characteristic obstacles in the terrain unit against the vehicle's configuration in a number of critical positions during crossing to see if the vehicle can pass over without a hang-up or a nose-in type failure. If either type of failure is indicated, NO-GO is assigned for the unit. If there is no failure the obstacle traction submodel is exercised. The "obstacle loop" indicated on Figure 3 means that the calculations nested in this loop are performed both for the case when all obstacles are crossed and for the case when all obstacles are avoided.

In the obstacle traction submodel the force required to overcome the obstacle is calculated. If the sum of this force plus the resistance due to soil and slope is less than the maximum achievable tractive force plus the effective force due to the vehicle's kinetic energy, a GO condition is indicated. (The "speed over obstacles at 2.5g" is needed to calculate the kinetic energy.)

Once it is determined that the vehicle can cross an obstacle, the obstacle override submodel computes an average resisting force from the force required to cross one obstacle and the average spacing of the obstacles. In the resistance versus speed submodel, average resistance due to obstacles is added to the resistance due to soil and slope

and to the average resistance due to vegetation (to be described later). The result represents the total resistance which must be overcome by the achievable tractive force. If the maximum achievable tractive force is greater than the total resistance (the GO condition), the submodel computes the "speed limited by total resistance", at which speed the achievable traction and the resistance are equal. The least of the latter speed, the speed limited by visibility, and of the speed limited by absorbed power (from the surface roughness submodel) is taken by the speed selection submodel and is called the "maximum speed between obstacles".

Let us now turn to the obstacle avoidance submodel. If all obstacles in the terrain unit are avoided, the vehicle must maneuver around them. The percentage of the terrain unit area accordingly denied to the vehicle is computed in the obstacle avoidance submodel. The percentage of area similarly denied to the vehicle due to the avoidance of one or more classes of trees in the terrain unit is computed in the vegetation avoidance submodel. The maneuvering (area denied) submodel then computes a "speed reduction factor" to account for the total reduction in speed associated with the denial of area due to avoidance of both obstacles and vegetation.

In the vegetation loop, repeated computations are performed to select a strategy for choosing among various possible tree avoidance and override combinations. First, it is assumed that all trees are avoided. Next, it is assumed that trees of the smallest stem size class are bowled over, and all larger trees are avoided. Then it is assumed that trees of the two smallest classes are overriden and the larger ones are avoided, and so on, until speed predictions corresponding to all possible choices from avoiding all trees to knocking down all trees have been produced. There are nine such options in all. Since each of these options is examined for each combination of (1) obstacles avoided or obstacles overriden and (2) uphill, level ground or downhill operation, the nested vegetation-obstacle-slope computation loop (see Figure 3) actually produces 9x2x3 - 54 speed predictions for each terrain unit.

The vegetation override submodel produces three different resistance values required for each speed prediction: (1) the average force required to fell a single tree (called the maximum vegetation override force), (2) the maximum force required while overriding one tree, and (3) the "average resistance due to vegetation". The latter value is calculated from the average force required to override one tree and the average distance between trees. The average resistance due to vegetation is used (as explained earlier) in the calculation of the "maximum speed between obstacles".

If the maximum vegetation override force divided by the vehicle weight is greater than 2, NO-GO is indicated because it is assumed that 2g horizontal deceleration represents the maximum human tolerance level. A further check is made to see whether the maximum vegetation override force is less than the pushbar force that the vehicle can stand. Thus, the vegetation impact submodel contains two checks and two types of possible NO-GO's.

The acceleration-deceleration submodel compares the maximum speed between obstacles to the speed calculated in the obstacle impart submodel, which limits vertical accelerations over single obstacles to 2.5g. If the speed over obstacles at 2.5g is larger than the speed between obstacles, the latter is the controlling speed.

But if the speed limited by vertical acceleration is less than the speed between obstacles, the vehicle is not allowed to maintain a constant speed. After the obstacle is crossed the vehicle can accelerate up to the "between obstacles speed", but it must begin to slow down in time to move with the speed limited by $2\frac{1}{2}$g vertical acceleration when the next obstacle is reached. The average speed which the vehicle can maintain is travelling over and between obstacles in the terrain unit under these constraints is computed in the acceleration/deceleration submodel. The accelerating force is taken from the tractive force versus speed array produced by the soil submodel, and the braking force is an output of the slope submodel.

Thus, a speed is computed for each assumed combination of obstacle-vegetation avoidance, under each assumed slope condition.

Next, that obstacle-vegetation avoidance combination which produces the highest speed is selected for each slope condition. From the three corresponding speed values, designated "speed for each slope", an average speed is then calculated assuming that 1/3 of the travel distance is upslope, 1/3 is downslope and 1/3 of the distance is on horizontal ground.

This speed is stored, along with the terrain unit number, and the overall process, beginning with the soil model, is repeated for each terrain unit described in the input data.

Several terrain areas have been mapped according to the AMC '71 Model by the U.S. Army Engineer Waterways Experiment Station. These are about 5 km wide and 40-50 km long. The number of different terrain units in the most complex of these areas is almost 1500. Thus, for that area, the part of the AMC '71 Model just discussed (the areal terrain module) produces some 1500 speed predictions.

Such a matrix of predicted speeds lends itself to various statistical or deterministic analyses which can be tailored to the needs of the user. Before discussing examples of the exploitation of the speed matrix, however, we will describe the rest of the model.

3. Linear-Terrain Module.

As presently structured, the linear module (for stream crossing module) assumes that, one way or another, the vehicle will cross any linear feature. In situations where

the vehicle cannot do this unaided, various expedients are assumed to be brought into play, such as winching, manual digging, rafting, etc.

The stream-crossing module computes two elements of crossing time. The first is the time required to cross the stream itself; the second is the time needed to negotiate the banks of the stream (see Figure 4).

The vehicle may either ford, swim, or be rafted across the river, depending upon stream and vehicle characteristics. If the stream current exceeds 11 mph, swimming is considered impractical, rafting is assumed, and a time penalty is levied.

Vehicles may experience hang-ups or nose-in failures on entry banks. If this happens, a time penalty is assigned for digging away the obstrusive part of the bank.

Egress performance is computed on the basis of the bank "severity factor" (14). If the vehicle cannot negotiate the bank on its own, winching is considered if applicable, or engineering aid is called. Time penalties are assigned in either case.

The stream crossing module of the AMC '71 Vehicle Mobility Model assumes that bridges are not available and that the vehicle travels by itself. The routine does not incorporate searching for a fording site or for more favorable bank conditions. When crossing times for a complete linear feature network are mapped, however, sections where crossing is least difficult become evident. Displaying available bridges on such a map is a simple matter.

Work is underway to produce an improved stream-crossing model which will include a more fundamental exiting model. It will also be compatible with a flexible output

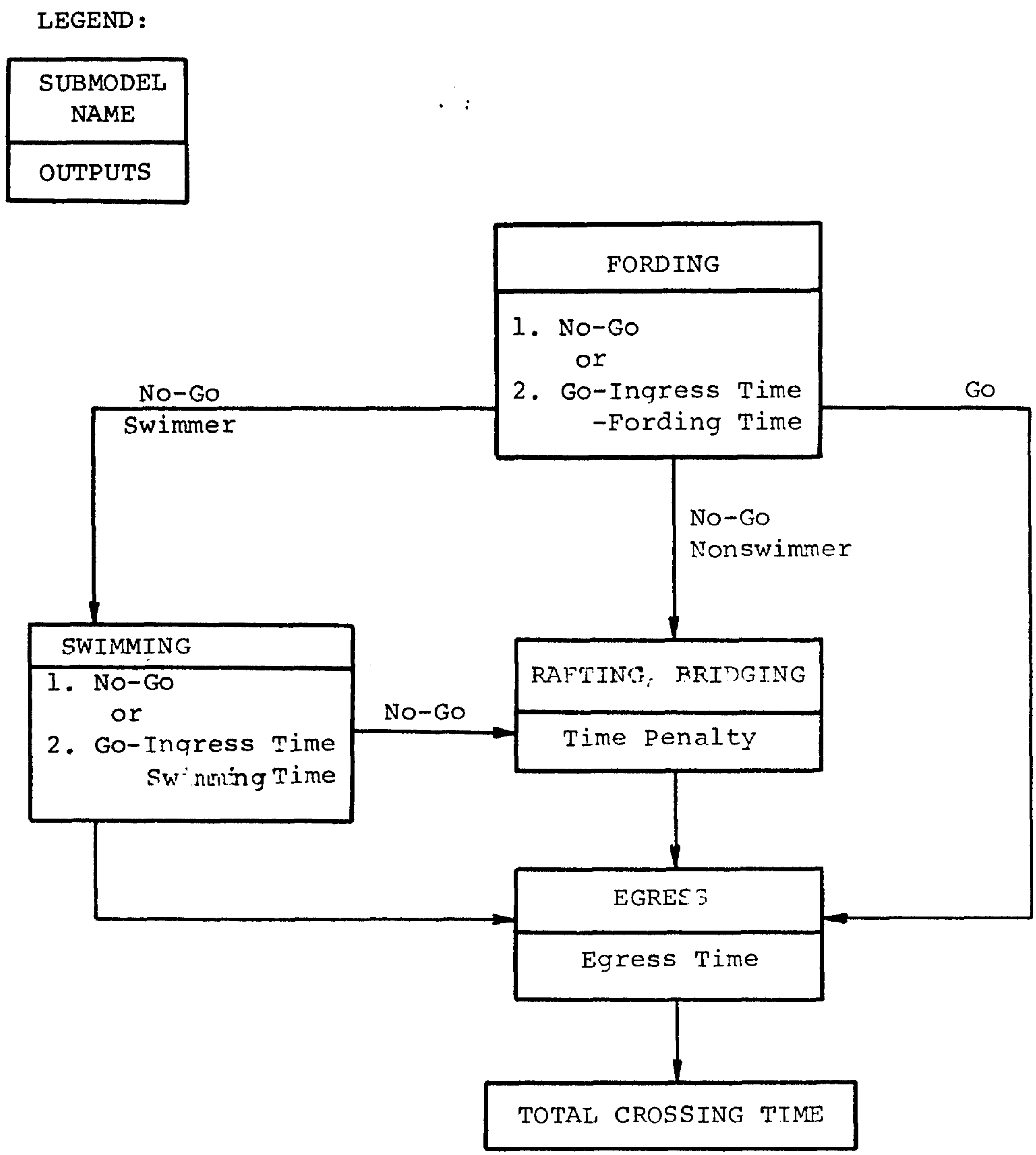


Fig. 4. Schematic flow diagram of linear terrain unit performance prediction module.

module in which the manner that crossing difficulties are handled may be varied to suit any given mission and scenario. The more fundamental exiting model will rigorously simulate the mechanics of a vehicle as it negotiates a complex bank slope. Buoyancy forces, inertia forces and reaction forces due to soft and slippery slopes will be included.

4. Output Modules.

The basic output of AMC-71 is a listing of areal and linear terrain units and corresponding speeds or crossing times. These data will generally require further organization before they become meaningful in context of specific problems. They may be displayed on maps, aggregated in various statistics, or used in selection or assessment of routes under various constraints and mission requirements. Thus, the further processing is very much user oriented.

Two specific output processing routines or modules have been developed and are discussed below. The first yields the best route across an area and the second evaluates mobility over a broad terrain area.

a. Route Selection Module.

The route selection module determines the optimum route across an area. The optimum route between A and B is defined as the one which requires the shortest time among all possible routes, and hence, yields the highest speed-made-good.

The speed-made-good over a route from A to B is the time taken to traverse from A to B (along the particular route followed) divided into the straight-line distance $\overline{AB}$.

No claim is made that the mathematically determined optimum route is related in any unique way to the

route that a driver would select if confronted with the real environment. It is asserted, however, that speed-made-good values thus computed for a specific vehicle represent a meaningful measure of the vehicle's overall mobility in a given area.

The significance of the weighting effect provided by the optimum route concept is best illustrated by an example. Calculations were made of optimum route and speed-made-good for three different tank concepts across a 4- by 40-km area in the Puerto Rico lowlands. The three tanks had tracks 22, 28 and 34 inches in width, respectively, but were identical in all other aspects. The soft-soil performance of these hypothetical designs varied considerably. (The one-pass vehicle cone index ranged from 80 to 59.) Nevertheless, the optimum speed-made-good values for the three configurations were identical. Why? Because, in the terrain considered, these vehicles all could avoid those areas where soft soil demanded wide tracks, and there was no advantage (in the assumed operation) to the vehicles with greater soft-soil capability in challenging soft-soil areas rather than avoiding them.

Thus, the optimum speed-made-good is a measure which accounts for vehicle characteristics and the distribution of terrain factors. However, because the simulation selects a single path, significant areas presenting difficult mobility problems may be neglected. Consequently, average speed-made-good values derived by averaging traverse times for the best route, the second best route, the nth, etc., best route, or by averaging traverse trials for the optimum routes between a number of selected pairs of points in the terrain, might be of greater practical significance for certain applications, and should be examined in future studies.

The route selection output module works as follows. The terrain area under consideration is overlaid with a rectangular grid, and only straight line motion is permitted between points having adjacent abscissas. Figure 5

depicts a rectangular terrain area subdivided by a 5x31 grid. One of the many possible paths is shown as a continuous series of vectors. In this example, the number of possible routes is 5^{31}.

One requires an extremely efficient searching technique to find the best from such an astronomical number of candidates. The AMC-71 Model does this by means of a scheme which employs dynamic programming (15).

First, we must calculate the time needed to move from any grid point C to any grid point D which lays on the ordinate immediately to the right of C. An example is shown in Figure 6.

The number of these path segments is 5 x 5 x 30 = 750 for the 5x31 grid shown in Figure 5.

These time intervals are stored in a matrix form in the computer.

The route selection computation begins at each grid point on the next-to-last ordinate. The fastest route from the next-to-last ordinate to the last ordinate is easily found. Once this information is known, the computer moves to the ordinate which is two steps removed from the last one. It is simple to find the fastest route from here to the end because the information obtained before allows one to drastically reduce the number of comparisons required.

The computational scheme moves to the left gradually until the best route is known from the starting line to the end.

It can be shown that for the 5x31 grid, the number of time element comparisons required is 5 x 5 x 30 = 750, instead of 5^{31}. The latter would pose an absurd computer time requirement (millions of years) while 750 comparisons is a trivial task for a modern computer.

Table 1 depicts an output sheet of the best route selection output module. As it is seen, the program furnishes other data besides the coordinates of the best route. Under the heading "Performance by Number of Patches", the computer lists the percent of terrain units in which the vehicle would experience NO-GO, the percentage of units where the vehicle can proceed with speeds up to 2 mph, and so on.

This information furnishes a valuable picture of the distribution of the vehicle's mobility over the entire area. However, the fact that the vehicle can move with speeds greater than 10 mph in 46.2% of the terrain units, for example, does not mean that this is true for 46.2% of the total area. Since terrain units may differ considerably in area, it is entirely feasible that 46.2% of the terrain units may cover 10% of the area, they may cover 99% of the area.

To derive from the data in Table I, the distribution of speeds with respect to terrain area, one would have to measure the area of each terrain unit, which is a Sisyphean task. An estimate may be used instead. As an example, five straight-line traverses may be laid out running the length of the transect.

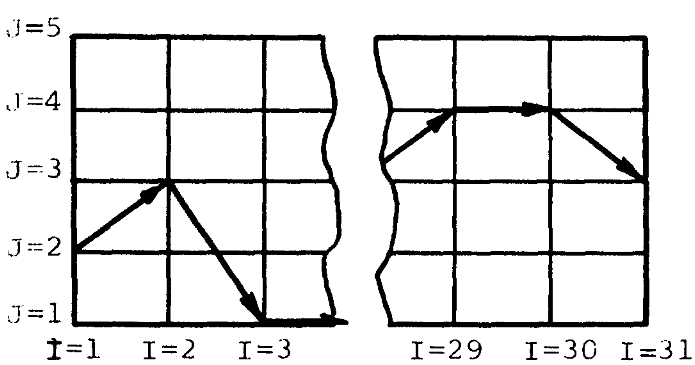


FIGURE 5

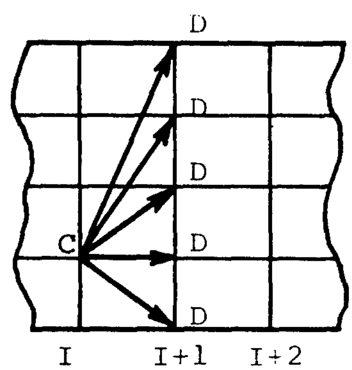


FIGURE 6

TABLE I

PERFØRMANCE BY NUMBER ØF PATCHES

10.5 %	14.5 %	4.3 %	3.6 %	3.6 %	17.3 %	46.2 %
0.0	0 TØ 2	2 TØ 4	4 TØ 6	6 TØ 8	8 TØ 10	> 10

VELØCITY RANGE--MPH

PERFØRMANCE BY AREA

5.2 %	38.5 %	3.5 %	2.1 %	2.5 %	11.4 %	36.9 %
0.0	0 TØ 2	2 TØ 4	4 TØ 6	6 TØ 8	8 TØ 10	> 10

VELØCITY RANGE--MPH

```
FRØM  1  TØ  3  ØN  SEG   1  IN    46.28  MIN
FRØM  3  TØ  2  ØN  SEG   2  IN    74.72  MIN
FRØM  2  TØ  2  ØN  SEG   3  IN     7.46  MIN
FRØM  2  TØ  3  ØN  SEG   4  IN     4.31  MIN
FRØM  3  TØ  2  ØN  SEG   5  IN     3.42  MIN
FRØM  2  TØ  1  ØN  SEG   6  IN     3.90  MIN
FRØM  1  TØ  1  ØN  SEG   7  IN     1.12  MIN
FRØM  1  TØ  2  ØN  SEG   8  IN    12.15  MIN
FRØM  2  TØ  3  ØN  SEG   9  IN    73.24  MIN
FRØM  3  TØ  4  ØN  SEG  10  IN    66.40  MIN
FRØM  4  TØ  5  ØN  SEG  11  IN    14.83  MIN
FRØM  5  TØ  5  ØN  SEG  12  IN    11.53  MIN
FRØM  5  TØ  5  ØN  SEG  13  IN     3.84  MIN
FRØM  5  TØ  5  ØN  SEG  14  IN    99.58  MIN
FRØM  5  TØ  5  ØN  SEG  15  IN     4.33  MIN
FRØM  5  TØ  5  ØN  SEG  16  IN     4.77  MIN
FRØM  5  TØ  5  ØN  SEG  17  IN     4.84  MIN
FRØM  5  TØ  3  ØN  SEG  18  IN     8.33  MIN
FRØM  3  TØ  1  ØN  SEG  19  IN     6.54  MIN
FRØM  1  TØ  2  ØN  SEG  20  IN     5.61  MIN
FRØM  2  TØ  2  ØN  SEG  21  IN     3.72  MIN
FRØM  2  TØ  1  ØN  SEG  22  IN     2.64  MIN
FRØM  1  TØ  1  ØN  SEG  23  IN     1.10  MIN
FRØM  1  TØ  1  ØN  SEG  24  IN     0.71  MIN
FRØM  1  TØ  2  ØN  SEG  25  IN     2.58  MIN
FRØM  2  TØ  3  ØN  SEG  26  IN    14.76  MIN
FRØM  3  TØ  2  ØN  SEG  27  IN     6.03  MIN
FRØM  2  TØ  2  ØN  SEG  28  IN     4.03  MIN
FRØM  2  TØ  2  ØN  SEG  29  IN     4.07  MIN
FRØM  2  TØ  1  ØN  SEG  30  IN     5.39  MIN
```

```
TØTAL TIME ØF TRAVERSE          8.37  HØURS
TØTAL LENGTH ØF TRAVERSE       22.72  MILES
AVERAGE SPEED ØF TRAVERSE       2.71  MPH
```

Total distance accumulated in any given terrain unit (which may occur many places throughout the sample, or only once), in ratio to the total length of the sample, may be assumed to represent the relative areal occurrence of that terrain unit in the transect. Table 2 shows part of a listing in which this sampling approach was used to assign relative weights to performance in a single terrain unit in arriving at a mean speed for all of the terrain in a transect. Column 3 shows the relative areal occupancy of each terrain unit (Column 2) in terms of the relative distance in the terrain unit recorded in the sample.

The procedure provides an estimate of relative occurrence, but remains an approximation on two counts: (1) only those terrain units are included which are intersected by the line samples; (2) the distribution relates to segment lengths, not to areas.

A detailed description of the computational scheme is given in Appendix C.

b. Speed Profile.

In this section we will briefly discuss the speed profile module, which provides a number of useful statistical interpretations of terrain unit speed data. The module utilizes the sampling procedure just described to estimate relative areal occupancy of terrain units. It is further assumed, necessarily without reference to areal distribution or configuration of specific terrain units, that a driver operating in a transect would try to avoid the most difficult areas. In accord with this, the output table of speed versus terrain unit number is ordered with terrain units in decreasing order of in-unit speed (Table 2, Column 5).

Column 4 shows the accumulated percent of distance from the beginning of the list (distance over which equal or higher speeds may be maintained), and Column 6 gives

TABLE 2

Columns								
1	2	3	4	5	6	7	8	9
	Terrain Unit	% Distance In Unit	Accum	Predicted In Unit	Speed Accum	Factor Up	Limiting Level	Speed Down
101	524	0.0	16.7	16.8	20.4	4	2	5
102	547	0.0	16.8	16.8	20.4	4	2	5
103	598	0.0	16.8	16.8	20.4	4	2	5
104	567	0.0	16.8	16.8	20.4	4	2	5
105	971	0.1	16.9	16.7	20.4	2	4	5
106	966	0.1	17.0	16.7	20.4	2	4	5
107	1179	0.1	17.1	16.2	20.3	2	6	6
108	1082	0.1	17.2	16.2	20.3	2	6	6
109	1126	0.0	17.2	16.2	20.3	2	6	6
110	1099	0.0	17.3	16.2	20.3	2	6	6
111	1109	0.0	17.3	16.2	20.3	2	6	6
112	1143	0.0	17.3	16.2	20.3	2	6	6
113	1139	0.0	17.3	16.2	20.3	2	6	6
114	1100	0.0	17.3	16.2	20.3	2	6	6
115	1173	0.0	17.3	16.2	20.3	2	6	6
116	1052	0.1	17.4	15.9	20.2	4	4	6
117	1259	2.6	20.0	15.3	19.4	2	2	5
118	1193	0.3	20.3	15.3	19.3	2	2	5
119	1256	0.1	20.4	15.3	19.3	2	6	5
120	1202	0.1	20.5	15.3	19.3	2	2	5
121	1201	0.1	20.5	15.3	19.3	2	2	5
122	1196	0.1	20.6	15.3	19.3	2	2	5
123	1225	0.1	20.7	15.3	19.2	2	2	5
124	1360	0.0	20.8	15.3	19.2	2	2	5
125	1361	0.0	20.8	15.3	19.2	2	2	5
126	1214	0.0	20.8	15.3	19.2	2	2	5
127	113	0.3	21.0	15.2	19.2	2	6	6
128	616	0.2	21.2	15.2	19.1	2	6	6
129	543	0.1	21.3	15.2	19.1	2	6	6
130	527	0.1	21.4	15.2	19.1	2	6	6
131	613	0.1	21.4	15.2	19.1	2	6	6
132	665	0.1	21.5	15.2	19.1	2	6	6
133	574	0.0	21.5	15.2	19.0	2	6	6
134	564	0.0	21.6	15.2	19.0	2	6	6
135	93	0.0	21.6	15.2	19.0	2	6	6
136	697	0.0	21.7	15.2	19.0	2	6	6
137	558	0.0	21.7	15.2	19.0	2	6	6
138	652	0.0	21.8	15.2	19.0	2	6	6
139	553	0.0	21.8	15.2	19.0	2	6	6

the corresponding average speed for that distance (total distance/total time). This is a theoretical speed the vehicle could attain by avoiding all terrain units in which the going is slower.

This organization permits the reader to see at a glance the percent of total area which can be negotiated at a given average speed (Columns 4 and 6) or at speeds greater than a given minimum speed (Columns 4 and 5).

From the output data organized as in Table 2, various statements may be made regarding the vehicle's capabilities in a transect as a whole. On the premise that some operations may require the ability to function over the entire area, the average speed in all of the areal terrain in a transect (denoted V_{100}) is an appropriate measure of a vehicle's suitability. For less demanding missions, it may be assumed that some portion (say 10 percent) of the area which is least favorable for a given vehicle may be ignored, in which case the average speed in the remaining 90% of the area (denoted V_{90}) might be a useful measure. The complete picture, in which the percent of area ignored takes on all values from 0-100 percent, can be usefully summarized in curve form, to provide a speed profile (Figure 7).

Table 2 also shows a further feature of this output routine. Columns 7, 8 and 9 contain codes indicating the terrain factor which limits the speed in the terrain unit when going upslope, across the slope ("level"), and downslope. The code is as follows: Code 1 is soil resistance, Code 2 is slope resistance, 3 is vegetation resistance, 4 is obstacle resistance, 5 is visibility, 6 is rough terrain, 7 is severe shock (2-1/2g vertical acceleration), 8 is area denied by vegetation, and 9 is area denied by obstacles.

From this identification a table may be created which depicts the percent of area where each factor

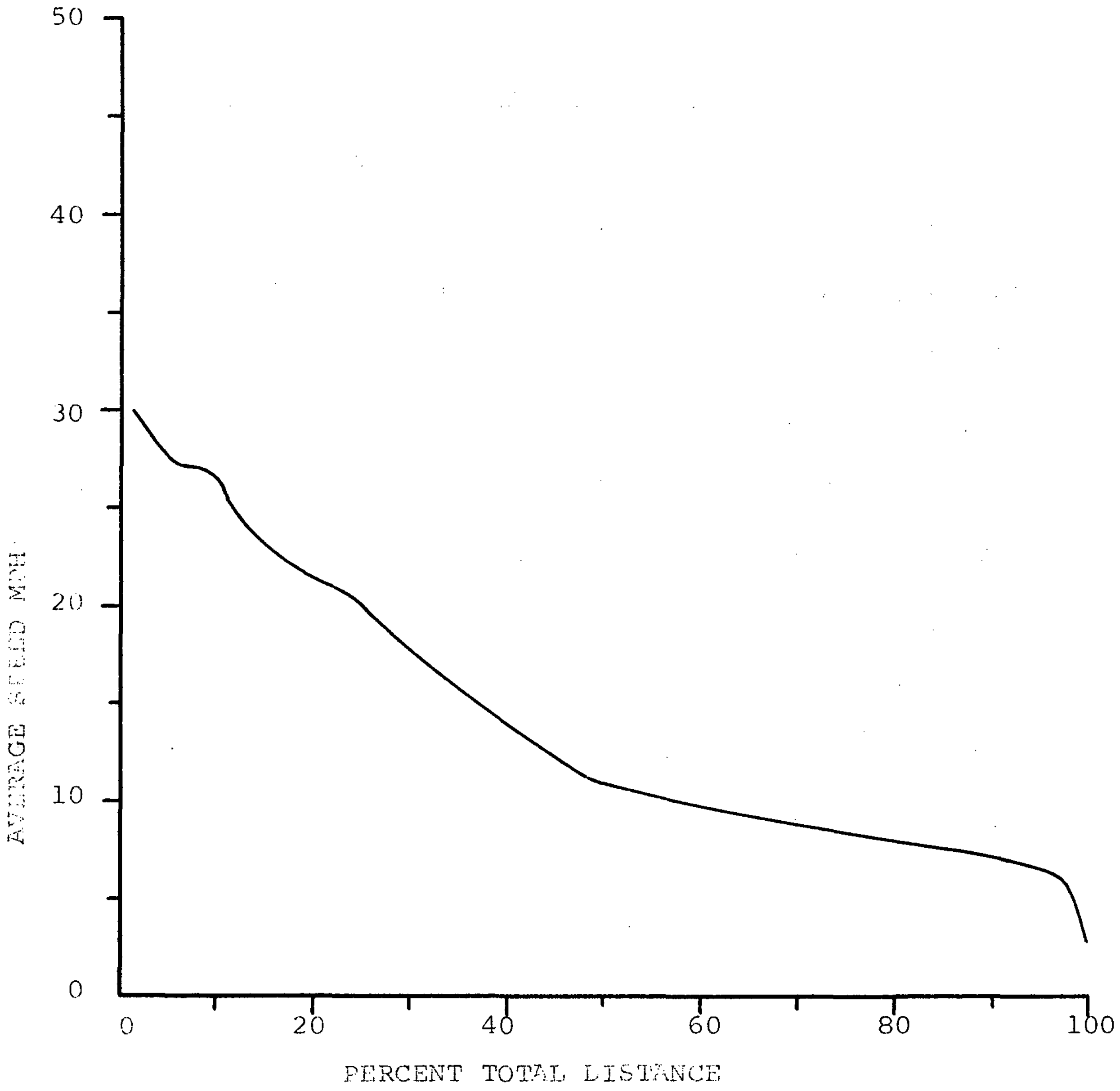


Fig. 7. Off-road **velocity** profile, M656 5-ton 8x8 truck.

TABLE 3

% OF TRAVERSE LIMITED BY EACH FACTOR

	1	2	3	4	5	6	7	8	9
M60	9	61	0	0	0	7	0	13	1
55T, TB&T, TUR	2	48	0	0	0	23	0	23	1
45T, TB, VCR	5	51	0	0	0	10	0	20	1
45T, TB&T, VCR	25	45	0	0	0	1	0	26	1
45T, TB&T, TUR	3	26	0	0	0	45	0	25	1
35T, TB, VCR	5	42	0	0	0	11	0	12	1
35T, TB&T, TUR	2	25	0	0	0	44	0	14	1
45T, TB, VCR wet	20	40	0	0	0	5	0	20	1
45T, TB&T, VCR wet	35	38	0	0	0	1	0	20	1
45T, TB&T, TUR dry	0	28	0	0	0	41	0	18	1

is the dominant speed-limiting influence (see Table 3). Such a table might show that in 70 percent of the cases rough terrain is the reason why the vehicle cannot run faster. If this is the case, improvements in the suspension system may be called for. If soft soil dominates as a speed control, then ground pressure, contact area, or engine performance should be scrutinized, and so on.

VIII. RESTRICTIONS AND LIMITATIONS

The more realistic a mathematical model is, the more accurate are the predictions it yields. There is, however, a point of diminishing return. If one attempts to include too many features of reality, the equations and/or the computational requirements become unwieldy. If, on the other hand, the model is too simple, or the input data are too crude, the model will be inaccurate and will fail to discriminate between systems having significant differences in performance. The model will not be sensitive enough.

To find the minimum level of complexity where a model's accuracy is acceptable, one needs to perform a series of experiments to measure pertinent system performance characteristics. The measured data can then be compared to a series of predictions obtained at different levels of model complexity and/or input data resolution.

At the time of this writing, data from field validation tests are few. Nevertheless, one can point with confidence at several assumptions and simplifications employed in AMC-71 which will certainly have to be scrutinized and possibly remedied.

It is emphasized, however, that several of the shortcomings listed below have been corrected since AMC-71 was established. Also, it is likely that field test data will

show that some of the assessments made in the ensuing paragraphs are too pessimistic.

a. In AMC-71, the terrain is made deterministic because it uses the mid-range value of each terrain factor class, thereby replacing nature's continuum by a step function. For this reason the possibility exists for assigning NO-GO to one or two vehicles and GO to the other on the basis of very small differences in vehicle characteristics. Conversely, vehicles with relatively large differences in critical characteristics may show no performance differences. Ground clearance furnishes the example easiest to understand. It is seen in Appendix A that vertical obstacles between 18 and 24 inches are all considered to be 20 inches high. Consequently, a vehicle with 19-1/2 inch ground clearance is NO-GO in a field which has dikes of 18-24 inches height but a vehicle with 20-1/2 inch clearance will be GO. This is an unwarranted amplification of a relatively small difference. The opposite can also occur; i.e., relatively large vehicle differences can result in no apparent performance advantage.

The next higher obstacle height class embraces obstacles in the range of 24-34 inches, for which a constant height of 28 inches is used. A vehicle with 20-1/2 inches in ground clearance will pass the first class, and fail on the next. Another vehicle with 27-1/2 inches ground clearance will do likewise.

b. In the model, vehicle vibrations due to ground influences and accelerations while crossing single obstacles are treated in two dimensions only, the vertical centerline plane, and within this plane, longitudinal vibrations and accelerations are not considered, and motions are not included. This causes inaccurate predictions because the vibratory power absorbed by the driver due to roll motion and longitudinal impacts is significant, and because if a step-like obstacle is not met "head on" even the motions upon which the 2-1/2g vertical acceleration criterion is based

will not be realistic. Further, in the analysis of the dynamics of the vehicle, the kinetic properties of tires and tracks are idealized and simplified. These simplifications warrant further scrutiny and, possibly, refinement.

c. The driver presently acts as a governor only, imposing speed limits based upon a fixed absorbed power, vertical and (in one case only) horizontal acceleration levels or upon forward visibility. Driver competence, experience or his ability to read the terrain and make right decisions is not taken into account.

d. It is assumed that when a vehicle crosses into another terrain unit, its speed jumps instantaneously to the velocity level predicted for the unit entered. This may cause significant errors in the prediction of the overall crossing time, particularly if the terrain units are small. Where the units are large, the driver will be able to move with steady speed most of the time and the effect of short periods of acceleration and deceleration will be negligible. Another simplifying assumption, relative to crossing areal terrain units, is that the vehicle is always moving along straight line segments. The time required for turning is not considered except as a part of the maneuvering required to thread through vegetation and obstacles within a terrain unit. Neither does the model allow for the mechanics and dynamics of terrain vehicle interaction while a curved path is being negotiated.

e. Performance is predicted for a single vehicle crossing the area at the highest possible speed. No provisions are made for moving in a convoy or in units, or for scenarios which call for less than maximum speed.

f. The soil submodel is based on am empirical system which has been verified to be of acceptable accuracy in a variety of soil conditions. A mathematical system based on fundamental soil properties and on the differential equations of soil-equilibrium and yield conditions would be more

general, accurate and flexible. (Also, it would be considerably more complex.) It should be mentioned at this point that the present model calculates tire traction performance on the basis of standard military nondirectional medium-skid cross-country tires. Another potential weakness in the soil sub-model is that the effect of distinct soil layers, including that of a "slippery" thin top layer, is not accounted for.

g. AMC '71 cannot handle articulated vehicles.

h. The visibility submodel appears to be overly simplistic.

i. Ground roughness and single obstacles are treated as unyielding or rigid. No tire or suspension compliance is considered in calculating obstacle interference. Although ground rough enough to cause severe vibrations is usually hard, neglecting soil deformation and its smoothing effect on ride may result in predictions which are too conservative. Dikes, trenches, ditches are seldom rigid in nature, so that a 16-inch dike, for example, would not stop a vehicle having 15-1/2 inch ground clearance. The model, in its present form, would, however, call NO-GO in this case while it would predict GO conditions for a vehicle having 16-1/2 inch ground clearance.

j. The riverine module is based on empirical formulas and intuitive rule-of-thumb expressions developed by experienced engineers. Furthermore, the module is scenario dependent. It automatically calls for outside help and/or other remedies when NO-GO is encountered and assigns time penalties. This will have to be modified so that the module yields crossing time predictions for all river classes (including NO-GO) and leaves it to the output module to account for such possibilities as looking for another crossing site or other expedients compatible with the mission scenario.

k. The output module (best route) does not allow for curved path motion and it "forces" the vehicle through the

node-points of a relatively coarse grid which is laid over the map. The grid can be made finer at the expense of required input data-preparation and computer core-time requirements, and mathematical algorithms which allow for more complex and flexible vehicle paths can be introduced, again at the expense of time and computer memory bank requirements.

l. Finally, it is pointed out that the entire computer program should be made more efficient, so as to require less running time, and should be made more modular so that sub-models can be used and/or altered without affecting the entire program.

As mentioned before, several of the above shortcomings are already being remedied. In particular, significant progress is being made in areas described in paragraphs b, f, g, j, k and l.

IX. APPLICATIONS

1. Four Vehicles in Puerto Rico.

In its first large scale trial application, the AMC '71 Mobility Model was exercised to examine the performance of four existing Army vehicles over a 4x40 kilometer terrain area in the Puerto Rican lowlands. Two vehicles, the M151, 1/4-ton Truck, and the M35A2M, 2-1/2 ton Truck and two tracked vehicles, the M113A1 Armored Personnel Carrier and the M60A1 Tank, were considered.

The Puerto Rican application was the first part of a larger exercise to examine the performance of these four vehicles in six different geographic areas which, taken together, constitute a terrain simple representative of a major fraction of the earth's strategically important areas.

The other five sites to be considered are located in Arizona, Alaska, Northern Europe, North Korea and Thailand.

Terrain data required to characterize the Puerto Rico study area for application of the model were derived by application of map and air-photo interpretation techniques described in Reference 16. A sample listing of the numerical values employed is given in Appendix A (see Page A28).

Required vehicle characteristics data for the simulated vehicles are tabulated in Appendix B.

Application of the terrain categorization scheme described in Appendix A subdivided the 4x40 kilometer terrain area into 1,080 unique areal terrain units (many occurring many times), plus 105 linear units (rivers and streams). (See Appendix A.) Speed predictions were made for each vehicle operated in each terrain unit under three different environmental conditions; wet, dry and average season. Thus, 1,185 x 4 x 3 = 14,220 individual terrain-unit speed predictions were obtained in all. Optimum route and associated speed-made-good calculations were also performed for each of the 12 vehicle/season combinations.

Results:

Table 4 contains a tabular presentation of the terrain-unit speed predictions for the first 55 terrain units. Twelve numbers are given for each terrain unit representing average speed, in miles per hour, in each season for the four vehicles considered.

Tables 5 and 6 present some data comparing the performance of the four simulated vehicles and illustrating the important seasonal effects. The presentations are in terms of elapsed time of optimum-route traverse, and associated speed-made-good, respectively.

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TABLE 4

PATCH TYPE	M60A1 DRY	M60A1 AVE	M60A1 WET	M113A1 DRY	M113A1 AVE	M113A1 WET	M35A2M DRY	M35A2M AVE	M35A2M WET	M151 DRY	M151 AVE	M151 WET
1	27.5	26.3	22.4	38.7	36.3	28.3	32.5	30.5	25.2	30.0	30.0	30.0
2	27.5	26.3	22.4	38.6	36.1	28.1	31.8	30.3	25.1	30.0	30.0	30.0
3	27.5	26.3	22.4	15.5	15.5	15.5	19.0	19.0	19.0	20.0	20.0	20.0
4	27.5	26.3	22.4	32.0	31.6	27.2	25.0	25.0	24.1	30.0	30.0	30.0
5	27.5	26.3	22.3	15.5	15.5	15.5	19.0	19.0	19.0	20.0	20.0	20.0
6	27.3	26.2	22.0	15.5	15.5	15.5	19.0	19.0	19.0	20.0	20.0	20.0
7	27.5	26.3	22.3	15.5	15.5	15.5	19.0	19.0	19.0	20.0	20.0	20.0
8	27.2	26.1	21.9	38.4	35.6	27.6	31.6	29.9	25.0	30.0	30.0	30.0
9	26.9	25.9	21.6	32.0	31.4	26.8	25.0	25.0	24.1	30.0	30.0	30.0
10	27.4	26.2	22.2	15.5	15.5	15.5	19.0	19.0	19.0	20.0	20.0	20.0
11	27.1	26.1	21.8	15.5	15.5	15.5	19.0	19.0	19.0	20.0	20.0	20.0
12	13.7	13.7	13.7	18.2	18.2	18.2	17.8	17.8	17.7	17.8	17.8	17.8
13	8.6	8.6	8.6	11.0	11.0	11.0	10.8	10.8	10.7	10.8	10.8	10.7
14	26.6	25.3	21.1	31.3	27.3	22.7	27.2	25.4	20.4	30.0	30.0	30.0
15	8.6	8.6	8.6	11.0	11.0	11.0	10.8	10.8	10.7	10.8	10.8	10.7
16	4.7	4.7	4.7	5.6	5.6	5.6	5.5	5.5	5.5	5.5	5.5	5.5
17	2.0	2.0	2.0	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
18	26.6	25.2	21.1	15.5	15.5	15.5	19.0	19.0	18.6	20.0	20.0	20.0
19	26.5	25.1	21.0	28.5	26.1	22.2	24.5	24.0	19.5	30.0	30.0	30.0
20	13.7	13.7	13.7	18.2	18.2	18.2	17.8	17.8	17.5	17.8	17.8	17.8
21	8.6	8.6	8.6	11.0	11.0	11.0	10.8	10.8	10.7	10.8	10.8	10.7
22	8.6	8.6	8.6	11.0	11.0	11.0	10.8	10.8	10.7	10.8	10.8	10.7
23	26.4	24.8	20.8	15.5	15.5	15.5	19.0	19.0	18.0	20.0	20.0	20.0
24	8.6	8.6	8.6	11.0	11.0	11.0	10.8	10.8	10.7	10.8	10.8	10.7
25	26.2	24.4	20.3	15.5	15.5	15.5	19.0	19.0	17.2	20.0	20.0	20.0
26	8.6	8.6	8.6	11.0	11.0	11.0	10.8	10.8	10.7	10.8	10.8	10.7
27	6.9	6.9	6.9	8.5	8.5	8.5	8.3	8.3	8.3	8.3	8.3	8.3
28	25.8	24.0	19.9	23.2	22.0	21.0	22.3	20.5	16.9	30.0	30.0	29.9
29	8.6	8.6	8.6	11.0	11.0	11.0	10.8	10.8	10.7	10.0	10.0	10.0
30	13.7	13.7	13.7	18.2	18.2	17.3	16.4	15.9	14.5	10.2	10.2	10.2
31	8.6	8.6	8.6	11.0	11.0	11.0	10.8	10.8	10.7	10.8	10.8	10.7
32	26.5	24.9	20.9	30.9	27.0	22.5	27.0	25.3	20.2	30.0	30.0	30.0
33	20.0	20.0	19.7	3.7	3.7	3.7	9.0	9.0	9.0	7.5	7.5	7.5
34	26.3	24.6	20.5	28.7	26.2	22.3	24.7	24.1	19.9	30.0	30.0	30.0
35	16.3	16.3	16.3	7.0	7.0	7.0	5.9	5.9	5.9	5.5	5.5	5.5
36	18.9	18.9	18.9	7.0	7.0	7.0	7.0	7.0	7.0	6.1	6.1	6.1
37	16.3	16.3	16.3	7.0	7.0	7.0	5.9	5.9	5.9	5.5	5.5	5.5
38	2.0	2.0	2.0	7.0	7.0	7.0	1.7	1.7	1.7	1.9	1.9	1.9
39	24.1	23.5	21.2	7.0	7.0	7.0	6.5	6.5	6.5	6.4	6.4	6.4
40	25.2	24.0	20.8	10.1	10.1	10.1	10.3	10.3	10.3	10.3	10.3	10.3
41	10.8	10.8	10.8	9.6	9.6	9.6	7.5	7.5	7.5	7.2	7.2	7.2
42	16.3	16.3	16.3	7.0	7.0	7.0	4.1	4.1	4.1	3.9	3.9	3.9
43	25.2	24.6	21.2	10.1	10.1	10.1	10.3	10.3	10.3	12.3	12.3	12.3
44	8.7	8.7	8.7	7.0	7.0	7.0	5.8	5.8	5.8	6.2	6.2	6.2
45	16.3	16.3	16.3	7.0	7.0	7.0	4.1	4.1	4.1	3.3	3.3	3.3
46	13.7	13.7	13.7	10.1	10.1	10.1	9.6	9.6	9.6	9.2	9.2	9.2
47	16.3	16.3	16.3	7.0	7.0	7.0	4.1	4.1	4.1	3.9	3.9	3.9
48	13.7	13.7	13.7	7.0	7.0	7.0	4.1	4.1	4.1	3.3	3.3	3.3
49	24.6	23.5	20.0	23.8	20.8	17.2	21.3	19.9	16.0	26.0	26.0	26.0
50	16.3	16.3	16.3	2.0	2.0	2.0	5.0	5.0	5.0	4.6	4.6	4.6
51	25.8	24.6	21.2	4.3	4.3	4.3	8.8	8.8	8.8	9.7	9.7	9.7
52	25.8	24.6	21.2	4.3	4.3	4.3	8.8	8.8	8.8	9.7	9.7	9.7
53	6.9	6.9	6.9	1.9	1.9	1.9	4.7	4.7	4.7	4.5	4.5	4.5
54	8.4	8.4	8.4	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.7
55	27.4	26.3	22.2	15.5	15.5	15.5	19.0	19.0	19.0	20.0	20.0	20.0

TABLE 5

TOTAL TIME OF TRAVERSE - HOURS

	TRACKED		WHEELED	
SEASON	M60A1	M113A1	M35A2M	M151
DRY	6.65	9.74	16.58	22.17
AVE	6.71	9.76	16.86	22.03
WET	8.37	9.96	NO-GO	22.06

TABLE 6

SPEED MADE GOOD - MPH (course length 22.72 miles)

	TRACKED		WHEELED	
SEASON	M60A1	M113A1	M35A2M	M151
DRY	3.42	2.33	1.37	1.02
AVE	3.39	2.33	1.35	1.03
WET	2.71	2.28	NO-GO	1.03

Discussion:

Tables 5 and 6 show that the tracked vehicles performed better than the wheeled vehicles in all cases studied. The results also indicate that the mobility of the M60 Tank is superior to that of the M113 Armored Personnel Carrier over the Puerto Rico terrain, and that the mobility of the 6x6 M35 Truck is superior to that of the 4x4 M151 Truck (except in the wet season, when the M35 becomes NO-GO in two segments).

It should be emphasized that the results summarized in Tables 5 and 6 are not characteristic of the simulated vehicles per se, but of their performance in their particular terrain environment considered, and further, that the terrain-vehicle interaction produces effects which cannot be accounted for by independent analysis of individual performance factors. The latter point can be illustrated by comparing the predictions for the M35 Truck during the wet and average seasons.

The only differences in the terrain input data for the two seasons are that the severity class describing the soil strength is larger by one for each terrain patch having fine-grained soil, and smaller by one for each patch having coarse-grained soil. Whereas these differences correspond to variations in soil trafficability which do not appear qualitatively significant when the vehicle is considered in terms of traditional mobility characterizing parameters, their synergistic effect on the M35's slope-climbing ability is in fact critical for the terrain area under study. It may be seen from Table 7 that the M35 vehicle is unable to negotiate either terrain section 7 or terrain section 29 during the wet season (as indicated by the notation, "10,000.00 min.," in the corresponding table entries). This means that the optimum route selection submodel has examined all 25 allowable traverse segments across each of these sections, and found each to be impassable.

Closer scrutiny of the computations associated with the prediction of the M35's wet season performance across

TABLE 7

PERFØRMANCE BY NUMBER ØF PATCHES

20.0 %	3.5 %	12.4 %	4.5 %	7.5 %	10.1 %	41.9 %
0.0	0 TØ 2	2 TØ 4	4 TØ 6	6 TØ 8	8 TØ 10	> 10

VELØCITY RANGE--MPH

PERFØRMANCE BY AREA

12.3 %	1.2 %	36.7 %	3.4 %	6.8 %	6.8 %	32.8 %
0.0	0 TØ 2	2 TØ 4	4 TØ 6	6 TØ 8	8 TØ 10	> 10

VELØCITY RANGE--MPH

```
FRØM  1 TØ  2 ØN SEG  1 IN    52.99 MIN
FRØM  2 TØ  1 ØN SEG  2 IN   142.48 MIN
FRØM  1 TØ  3 ØN SEG  3 IN    22.89 MIN
FRØM  3 TØ  4 ØN SEG  4 IN    11.32 MIN
FRØM  4 TØ  2 ØN SEG  5 IN     6.16 MIN
FRØM  2 TØ  2 ØN SEG  6 IN     3.70 MIN
FRØM  2 TØ  2 ØN SEG  7 IN 10000.00 MIN
FRØM  2 TØ  2 ØN SEG  8 IN    13.25 MIN
FRØM  2 TØ  1 ØN SEG  9 IN     9.32 MIN
FRØM  1 TØ  2 ØN SEG 10 IN     8.96 MIN
FRØM  2 TØ  2 ØN SEG 11 IN   435.43 MIN
FRØM  2 TØ  2 ØN SEG 12 IN    96.65 MIN
FRØM  2 TØ  1 ØN SEG 13 IN    83.81 MIN
FRØM  1 TØ  4 ØN SEG 14 IN   111.84 MIN
FRØM  4 TØ  5 ØN SEG 15 IN    12.09 MIN
FRØM  5 TØ  5 ØN SEG 16 IN     4.19 MIN
FRØM  5 TØ  4 ØN SEG 17 IN    11.17 MIN
FRØM  4 TØ  1 ØN SEG 18 IN    12.55 MIN
FRØM  1 TØ  2 ØN SEG 19 IN     3.08 MIN
FRØM  2 TØ  2 ØN SEG 20 IN     3.80 MIN
FRØM  2 TØ  2 ØN SEG 21 IN     6.56 MIN
FRØM  2 TØ  1 ØN SEG 22 IN     2.47 MIN
FRØM  1 TØ  1 ØN SEG 23 IN     0.88 MIN
FRØM  1 TØ  1 ØN SEG 24 IN     0.68 MIN
FRØM  1 TØ  3 ØN SEG 25 IN     4.29 MIN
FRØM  3 TØ  3 ØN SEG 26 IN     3.47 MIN
FRØM  3 TØ  3 ØN SEG 27 IN    12.40 MIN
FRØM  3 TØ  2 ØN SEG 28 IN    10.01 MIN
FRØM  2 TØ  2 ØN SEG 29 IN 10000.00 MIN
FRØM  2 TØ  1 ØN SEG 30 IN     5.67 MIN
```

```
TØTAL TIME ØF TRAVERSE       351.53 HØURS
TØTAL LENGTH ØF TRAVERSE      22.72 MILES
AVERAGE SPEED ØF TRAVERSE      0.06 MPH
```

terrain section 7 reveals two important points. First, it is found that the impassability of the allowable traverse segments is indeed due to the combined effect of soil weakness and ground slope. For example, the prevailing combination of soil class (i.e., RCI = 80 in the wet season, as opposed to RCI = 130 in the average season) and slope class (50 percent slopes, unchanged from season to season) control performance in terrain-unit 695, where the M35 "gets stuck" trying to cross section 7.

The second important point to be noted from close examination of the M35 best-route predictions for terrain section 7 is that the grid size arbitrarily selected for this first application was too coarse. Visual inspection of the Puerto Rico terrain map (Appendix A) shows that there indeed <u>are</u> paths across section 7 that the M35 can negotiate in the wet season. However, these paths are so circuitous that a straight line approximation thereto requires a much finer grid* than the one employed.

2. <u>WHEELS Study</u>

A more important application of the model was performed in support of the DA Staff WHEELS Study Group (17). WHEELS was a study with the purpose of evaluating the performance of individual standard military trucks both off and on road in relation to their missions and to cash savings possible through the substitution of commercial vehicles for military vehicles in some missions and the elimination of special military automotive features such as front wheel drive.

The AMC '71 Mobility Model was used in support of this study to assess the off and on road speed performance of a group of military and commercial vehicles and vehicles

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*At the time this report is published, techniques will have been established to allow motion in the J direction (see Figure 4) and to economically utilize much finer grids.

with trailers and howitzers, totaling 48 cases of direct interest plus 6 reference vehicles. (On-road speed performance was analyzed by means of a modified version of AMC '71 Model. Submodels which are not relevant to on-road performance, such as obstacle or vegetation negotiation, were eliminated while a "road curvature speed-limit" submodel was introduced.)

Several off-road terrain traverse speed predictions were made. These included speed over a combination of areal and linear terrains, identified as V_{110}, speed over areal terrain only (V_{100}) and speed over areal terrain with the worst 10 percent removed from consideration (V_{90}). (See Section VII, Item 4b on "speed profile").

Three geographic areas were considered: West Germany, Thailand and Arizona.

A large number of tables were constructed for the study group. These contained print-outs which emphasized predicted performance on-road, off-the-road but excluding river crossing, and finally, crossing both areal and linear features. These tables allow one to evaluate vehicles under appropriate mission conditions (e.g., highway operation mostly; off-road operation but no river crossing, and so on.)

Vehicles of comparable payloads were grouped for easy comparison.

X. ACKNOWLEDGMENT

This report describes the AMC '71 Mobility Model which was assembled under Task I of the AMC Vehicle Mobility Research Program.

The work was performed under the general direction of Mr. Paul F. Carlton, Chief of Environmental Sciences Branch, Research Division, Research, Development and Engineering Directorate, US Army Materiel Command. A Steering Committee was responsible for the overall guidance. The committee members included: Mr. D. E. Woomert from the Army Materiel Systems Analysis Agency; Mr. E. C. Hurford from the US Army CDC Combat Service Support Group; Mr. S. H. Miller from the Office of the Vice-Chief of Staff for Force Development; Mr. J. P. Carr from the Surface Systems Division, Research, Development and Engineering Directorate, US Army Materiel Command; and Mr. M. Kreipke and Dr. V. Zadnik from the Office of the Chief Research and Development. Mr. R. C. Navarin from Environmental Sciences Branch, US Army Materiel Command, took over the chairmanship of the committee in 1972.

The two principal agencies performing Task I, the compilation, programming and documentation of the AMC '71 Vehicle Mobility Model, were the Surface Mobility Division of the US Army Tank-Automotive Command headed by Mr. R. J. Otto, and the Mobility and Environmental Systems Laboratory of the US Army Engineer Waterways Experiment Station under Messrs. W. G. Shockley (Chief) and S. J. Knight (Assistant Chief).

The supervisor responsible for Task I was Mr. Z. J. Janosi of TACOM's Surface Mobility Division.

Other TACOM employees actively involved were as follows: Dr. J. Jellinek was assigned the responsibility for TACOM's share of the AMC 5-Year Mobility Research Program by the end of FY71; Mr. J. A. Eilers did the majority of the computer programming. Mr. F. Hoogterp also contributed significantly to the programming work and assembled the power train submodel. Mr. B. Hanamoto was instrumental in constructing the riverine submodel. Messrs. Z. J. Janosi and J. A. Eilers developed the application of dynamic programming technique for the best route selection submodel.

The Mobility and Environmental Systems Laboratory of the Waterways Experiment Station assembled the bulk of the flow charts and provided the necessary terrain input data. The former work was directed by Mr. A.A. Rula, Chief, Vehicle Studies Branch and the latter activity was headed by Mr. W. Grabau, Chief of the Terrain Analysis Branch. Mr. B. Schreiner of the Vehicle Studies Branch assembled the flow charts for the soft soil crossing submodels. He was assisted by Miss M.E. Smith of the Mobility Research Branch. The obstacle performance submodel was developed by Mr. J.G. Kennedy of the Vehicle Studies Branch and Mr. Eilers from TACOM. The vegetation submodel is the work of Mr. C.A. Blackmin of the Vehicle Studies Branch, while the late Mr. B. Stinson of the Vehicle Studies Branch prepared the flow chart for the areal terrain submodel. Mr. N.J. Murphy of the Mobility Research Branch was directly responsible for preparation and programming of the rough terrain, or vehicle dynamics, submodel. Other individuals from WES whose direct contribution was of significant importance were: Dr. A. Lessem (dynamics); Mr. E.S. Rush (mobility in soft soil); Mr. D.D. Randolph was responsible for the overall review and checkout of the program plus the writing of the text of several chapters in the appendices.

The report was prepared under the direction of Mr. H.J. Dugoff, Supervisor of Research and Analysis Functions for TACOM's Surface Mobility Division.

XI. REFERENCES

1. G. E. Bartlett, J. N. Deutschman: "Summary Report on Off-Road Mobility Research", Volumns I and II, CAL NO. VJ-2330-G-3, AD 690 169 and AD 690 170, Cornell Aeronautical Laboratory, Inc., Buffalo, New York (November 1968).

2. M. G. Bekker: "Introduction to Terrain Vehicle Systems", University of Michigan Press, Ann Arbor, Michigan (1969).

3. C. J. Nuttall, Jr.: "Ground Crawling (1966): The State-of-the-Art of Designing Off-Road Vehicles". Contract Report No. 3-162, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi (May 1967).

4. The Staff of the Land Locomotion Laboratory: "Research Report No. 6", U.S. Army Tank-Automotive Command, Warren, Michigan (November 1966), Technical Report 9560.

5. J. H. Grabau et al: "Mobility Environmental Research Study A Quantitative Method for Describing Terrain for Ground Mobility", Volumes I-VIII, Technical Report No. 3-726, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

6. P. L. Spanski: "Design and Fabrication, Mobility Exercise "A" Test Rigs", TACOM Report No. 9890 (LL 117), AD 839671L, U.S. Army Tank-Automotive Command, Warren, Michigan (December 1967).

7. J. K. Stoll, D. D. Randolph, A. A. Rula: "Relative Off-Road Mobility Performance of Six Wheeled and Four Tracked Vehicles in Selected Terrain", Technical Report M-70-4, U.S. Army Waterways Experiment Station, Vicksburg, Mississippi (April 1967).

8. M. G. Bekker: "Engineering Optimization of Terrain-Vehicle Systems", TACOM Report No. 10421 (LL 133), AD 854 107, U.S. Army Tank-Automotive Command, Warren, Michigan (February 1969).

9. Booz-Allen Applied Research Inc.: "Parametric Design/ Cost Effectiveness Study for an Armored Reconnaissance Scout Vehicle", (November 1968).

10. D. A. Sloss: "Estimated Exiting Performance for MICV and ARSV Concepts", Technical Memorandum, U.S. Army Tank-Automotive Command, Unpublished (10 September 1968).

11. A. A. Rula, C. J. Nuttall, Jr.: "An Analysis of Ground Mobility Models (ANAMOB)", Technical Report M-71-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi (July 1971).

12. Z. J. Janosi, J. S. Eilers: "Application of Dynamic Programming to Off-Road Mobility Problems", Proceeding of the 4th International Conference of the International Society for Terrain-Vehicle Systems, Stockholm, Sweden (April 1972).

13. F. Pradko, R. A. Lee, V. Kaluza: "Theory of Human Vibration Response", ASME Paper No. 66-WA-BHF-15, Winter Annual Meeting and Energy Systems Exposition, New York, New York (November 1966).

14. D. A. Sloss, et al: "Analysis of Estimated River Exiting Performance", TACOM Report No. 9689 (LL 115), U.S. Army Tank-Automotive Command, Warren, Michigan (July 1967).

15. R. E. Bellman: "Dynamic Programming", Princeton University Press, Princeton, New Jersey (1957).

16. R. E. Frost, et al: "Mobility Environmental Research Study, A Quantitative Method for Describing Terrain for Ground Mobility, Vol VI, Selected Air-Photo Patterns of Terrain Features", Technical Report No. 3-726, AD 484656, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi (May 1966).

17. USATACOM and WES: "Vehicle Mobility Assessment for Project WHEELS Study Group" (September 1972).

18. Appendix A of U.S. Army Combat Development Command Report: "Force Artillery Mix 1976", written by the Staff of the Mobility and Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi (unpublished).

19. "Ancilliary Study for Main Battle Tank Development Program", by the Surface Mobility Division of the U.S. Army Tank-Automotive Command, May 1972 (unpublished).

20. B.O. Benn: "An Analytical Model for Predicting Cross Country Vehicle Performance" Appendices A, B, C, D, E and F. Report No. TR-3-783, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi 1967.

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DOCUMENT CONTROL DATA - R&D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
1. ORIGINATING ACTIVITY (Corporate author) US Army Tank-Automotive Command Warren, Michigan 48090	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP	
3. REPORT TITLE The AMC '71 Mobility Model		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Report		
5. AUTHOR(S) (Last name, first name, initial) The Staffs of the Surface Mobility Division (TACOM) and the Mobility and Environmental Laboratory (WES).		
6. REPORT DATE June 1973	7a. TOTAL NO. OF PAGES 62 + 282 Appx.	7b. NO. OF REFS 20
8a. CONTRACT OR GRANT NO. b. PROJECT NO. 1TA161102B52A c. 1T662601A045 d. 1T162112A046	9a. ORIGINATOR'S REPORT NUMBER(S) Report No. 11789 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) LL-143	
10. AVAILABILITY/LIMITATION NOTICES Distribution of this document is unlimited.		
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY US Army Materiel Command	

13. ABSTRACT

This report presents the AMC '71 Mobility Model, a comprehensive computerized simulation of the interaction of a vehicle, a terrain and an operator. This model represents existing technology (as of 1971) for predicting the performance of wheeled or tracked vehicles across any type of terrain. While the model involves several simplifying assumptions necessitated either by lack of more complete information or by practical limitations on complexity and computer capacity, when used judiciously, it is a useful tool for ground mobility analysis even in its present form.

Following a brief introductory section, input requirements are discussed. Next is presented a narrative description of the model's structure including the simulation of dynamic effects and the crossing of areal terrain and linear terrains such as streams. The basic model output is shown to be a number of predicted speeds for a given single vehicle in each of a number of subunits of the terrains. Speeds in individual terrain subunits can be used for the development of various outputs depending on the needs of the user.

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DD FORM 1 JAN 64 1473

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Computer simulation						
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Principal restrictions and limitations of the model are given. Finally, two important applications are described in order to illustrate some of the possible uses of the model.

Appendix A contains the complete listing and definition of the necessary terrain input data. Appendix B includes the same for the vehicle inputs. Appendix C contains flow charts, program listings and the necessary background information in sufficient detail for a programmer to reproduce the AMC '71 Model.